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**DURIP APPLICATION OF MULTIPROCESSING TO REAL-TIME ANALYSIS  
AND CONTROL OF AN IONOSPHERIC RESEARCH RADAR**

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DURIP Application of Multiprocessing to Real-time Analysis and Control of an Ionospheric Research Radar

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INTRODUCTION

The utilization of high-frequency (HF) radio waves to probe the ionosphere was begun more than 50 years ago when the first swept frequency vertical incidence ionospheric sounder (ionosonde) was developed (*see Villard, 1976*). As technology evolved, so did the design of ionospheric sounders and several generations of sounders have been developed. As a result, the ionosonde has continued to remain a viable tool for the ionospheric physicist and vast amounts of ionospheric data have been collected. Over the past two decades, with the incorporation of digital technology into ionosondes, more sophisticated ionospheric sounders have been developed, with the capability of measuring the amplitude, phase, angle-of-arrival, polarization and Doppler shift in addition to the time-of-flight (ie. range) of the returned echo (*Wright and Fedor, 1969; Reinisch, 1986*). These systems have also employed digital recording techniques, markedly simplifying the analysis and interpretation of ionograms. Here, details of the NOAA digital ionospheric sounding radar and the Lowell University Digisonde will be discussed briefly as the design concepts are representative of state-of-the-art ionospheric sounders. — R H f

In the late 1970's, a digital HF ionospheric sounding radar (*Grubb, 1979*) was developed within the Space Environment Laboratory at the National Oceanic and Atmospheric Administration (NOAA). To a large degree, the design was influenced by research radars previously developed at NOAA by J.W. Wright and collaborators. The design philosophy led to the implementation of a distributed processing system, wherein the overall digital control for the transmitter and receiver subsystems was provided by an Interdata 7/16 minicomputer with 32K words of one microsecond core memory. Overall system timing and control was carried out using a 6502 microprocessor, and a special purpose bit-slice microprocessor was developed to perform signal processing. A 10 MB winchester disk drive and a 9-track 1600 bpi tape drive were used for program and data storage. All of the real-time radar operating system software was written in Interdata assembly language and software for control of the signal processing microprocessor (called the Front End Processor) was microprogrammed using an 84 bit word.

Details of the transmitter have been described by *Grubb (1979)*. Suffice it here to note that the low level RF drive is amplified by a solid state class A amplifier to the 200 watt level. This output can be used directly or can be used to drive a pulsed (60 microsecond pulse width) class A wideband vacuum tube amplifier with a 10 kW output. The transmitter output impedance is

nominally 50 ohms (unbalanced) and wideband balun transformers are used to drive the transmitting antenna.

The NOAA system was designed to support several operating modes. These include the swept-frequency mode (100 kHz - 30 MHz), a fixed-frequency mode (up to 10 sequential frequencies) and the partial reflection mode. Several different frequency ramps are available in the sweep-frequency mode. The system was designed to operate at repetition rates of 1, 10, 50 or 100 pulses per second. Two receiver channels are incorporated so that echoes are received simultaneously from pairs of dipole receiving antennas arranged on the sides of a square (*Paul*, 1982). A pulse set is comprised of four pulses, typically at frequency  $f$  (receive on North and South antennas), the next at  $f$  (receive on the East and West antennas), the third at  $f$  plus increment  $\Delta f$  (receive again on the East and West antennas) and finally at  $f + \Delta f$  (receive on the North and South antennas). Variations on this pattern and the configuration of the receiving array have been developed (*Jarvis and Dudeney*, 1986) in order to derive more accurately the polarization and to reduce the aliasing of Doppler velocities.

A total of six 'HF Radar' systems (also termed the Advanced Ionospheric Sounder and Dynasonde) were built by NOAA. During the 1980's, these systems have been operated in Antarctica (Siple and Halley Stations), Alaska, Quebec, Norway, New Mexico, Colorado and Utah. The customers for these instruments have been the British Antarctic Survey, the Max Planck Institute for Aeronomy, Utah State University and the U.S. Army. Two systems now reside at the Los Alamos National Laboratory, two at Utah State University, one at Halley Station (Antarctica) and one in Tromsø, Norway. Only the latter two systems remain as originally configured, although the radar at Halley will soon be converted to microcomputer control (see below).

The Digisonde was developed at Lowell University (*Bibl and Reinisch*, 1978; *Bibl et al.*, 1981) and has many features in common with the NOAA system. In both systems the transmitted signal is phase coherent, allowing signal (echo) phase to be measured; the receiver signal is digitized, which enables sophisticated signal processing techniques to be applied, and; spaced receiving arrays are utilized to measure wave polarization and angle-of-arrival. The Digisonde has three modes of operation: the swept-frequency (ionogram), Doppler-drift and fixed frequency mode. In the ionogram mode, the Digisonde can provide the automatic computation of the electron density profile through the application of true-height analysis (*Titheridge*, 1985, 1988). The Doppler-drift mode has been used extensively in the Northern polar cap region (*Reinisch*, 1986) and has been improved upon by the ionospheric group at La Trobe University (*Tedd*, 1989). The operating modes of the NOAA and Digisonde systems differ primarily in their statistical sampling philosophies in the time and frequency domains.

Approximately 16 Digisondes are operational throughout the world with another 20 in the planning or construction stage (*Reinisch et al.*, 1989). The USAF Air Weather Service has

purchased 18 of these systems for deployment at various locales both within and outside the continental United States. Six systems are currently operational and routinely transmit data to AWS Headquarters.

Several networks of ionospheric sounders have been developed, most notably by the Australian Ionospheric Prediction Service (IPS) and by the Communications Research Laboratory (CRL) in Japan. The Japanese network utilizes a Type 9-B ionosonde (*Koseki et al.*, 1980) manufactured in Japan and consists of 5 stations spaced 5° in latitude. Although the 9-B is not a digital system, the output of the ionosonde is digitized using a microcomputer and the data are transmitted to CRL Headquarters in Tokyo. There, automatic scaling software is utilized to extract the routine ionospheric parameters (*Igi et al.*, 1990) and the data from all stations are archived. The networking of ionosonde stations is, perhaps, most highly developed in Australia. For many years, the IPS has operated a network of 13 stations in the Australian region. Most of the stations in that network utilize the IPS model 5A ionosonde and plans are underway to upgrade these to the microcomputer controlled model 5B (*Paterson and Bevins*, 1989). The model 5B ionosonde generates a Gaussian transmitter pulse and incorporates receiver filters which match the transmitter pulse. The receiver output is digitized to 8 bits and separate frequency synthesizers are used to generate the transmitted and received signals over the range 1 - 21.475 MHz. All of the controlling microcomputers within the network use UNIX as the operating system and are connected to the main IPS computer using a 'star' network topology. The IPS ionosonde will continue to evolve in the future.

Several other groups have developed research ionospheric radars of which, in most cases, only a single instrument exists. Many of these instruments have been described in a recent paper by *Whitehead* (1989).

#### THE PC RADAR DESIGN

Recently, a new design for digital control of the NOAA radar has been developed by the Atmospheric Sciences group (*Argo and Hindman*, 1987) at the Los Alamos National Laboratory (LANL). This design, called the 'PC Radar,' is built around an IBM AT computer which replaces the functions of the Interdata 7/16 minicomputer for overall radar supervision. The PC Radar interfaces with the existing NOAA receiver and transmitter subsystems through the 8-bit digital input-output (DIO) bus and hence the upgrade merely requires a connection to this bus. Most of the features of the NOAA operating system are emulated by this design, which utilizes the high level 'C' programming language (in place of assembly language) for system control. As discussed by *Argo and Hindman*, this allows the operator considerable flexibility in configuring various sounding modes. For example, pulse coding and pulse averaging can be implemented and, with suitable antennas, the oblique sounding schemes of the type utilized by *Ruohoniemi et al.* (1989)

can also be utilized. Software for the implementation of the autocorrelation function used by the Applied Physics Laboratory in oblique HF radars at Goose Bay and Halley has been developed (but not tested) for the PC radar.

In addition to the system at Los Alamos, this design has been implemented on a NOAA ionospheric sounder at Utah State University and will shortly be used to upgrade the NOAA ionospheric sounder at Halley, Antarctica (operated by the British Antarctic Survey). The PC radar design has been implemented on a NOAA ionospheric sounder at Utah State University and will shortly be used to upgrade the NOAA ionospheric radar at Halley, Antarctica (operated by the British Antarctic Survey). The PC radar design will also be incorporated in a research instrument currently under development at the Naval Oceans Systems Center (NOSC) under the guidance of Dr. A.K. Paul. The NOSC system will differ little from the NOAA hardware configuration, primarily in that it will incorporate eight receiver channels.

Although a majority of the components are available 'off-the-shelf', the PC radar utilizes two special purpose boards which reside on the PC/AT bus. One board performs the analog-to-digital conversion of the quadrature (X,Y) output of the detectors in each receiver (ADC board) and the other is used to control the radar DIO bus (CRAM board). Two digital signal processing boards are utilized to replace functions performed by the FEP within the NOAA design. The SKY Computer signal processing boards (SKY321-PC) use the high speed (5 million instructions per second) Texas Instruments TMS32010 digital signal processor chip. These co-processing boards can be programmed, independently of the host computer, also using the C programming language. The CRAM card emulates the control functions of the 6502 microprocessor, which functioned as a 'timing sequence generator' in the NOAA design.

#### *USU PC RADAR IMPLEMENTATION*

Figure 1 shows a block diagram of the PC radar implementation developed at USU under the auspices of the AFOSR instrumentation grant. The dotted boxes denote those components utilized for system control and data analysis, while the diagonally hatched boxes indicate the existing receiver and transmitter subsystems associated with the NOAA HF ionospheric radar. Note that the configuration shown in Figure 1 is substantially enhanced over the design originally proposed. Specifically, we have added two additional microcomputers, one of which acts as a file server and the second as a real-time data analysis system, as well as additional mass storage devices. All three microcomputers, including the microcomputer dedicated to system control, communicate via a local area network (LAN). Archival data storage is provided by a 940 Megabyte (MB) optical disk drive which uses Write Once Read Multiple (WORM) technology. To the MS-DOS operating system, the WORM drive appears as an additional, albeit large, hard disk.

The ADC board digitizes the quadrature signals from the two receiver channels at 100 kHz and sends the data stream to the SKY Computer digital signal processing (DSP) boards (SKY 0 and SKY 1). Two DSP boards are required in order to keep up with the rate at which the ADC board transmits data. The DSP boards reside on the PC/AT bus and share memory space with the control microcomputer which is a DELL 310 (20 MHz 80386 cpu). As noted previously, the CRAM board provides the interface between the control microcomputer and the DIO bus used to send commands to the transmitter and receiver subsystems. Both the ADC and CRAM boards were purchased from a printed circuit board manufacturer and populated at USU with the appropriate components. Parenthetically, we note that additional ADC and CRAM cards were populated at USU (under separate contract) for the previously referenced hardware development now in progress at NOSC and at the British Antarctic Survey.

Recently, digital signal processing boards incorporating the third-generation Texas Instruments DSP chip (the TMS320C30) have appeared on the marketplace. This DSP chip is significantly faster than the first generation DSP chip used in the SKY Computer boards and also implements floating point arithmetic in contrast with the TMS32010, which allows only integer arithmetic. We have acquired a SPIRIT 30 DSP board from Sonitech International and anticipate utilizing this board at some time in the future. This board will enable more sophisticated signal processing to be carried out as the data are acquired. We note that utilization of the SPIRIT 30 requires a modified version of the ADC card (which is now under development at LANL).

As noted previously, rather than using a single PC/AT for the purposes of both control and data processing, we have acquired a DELL 316 (16 MHz 80386SX cpu) to be used for the analysis of data and a Televideo 80286 system to serve as a file server. These three computer systems will communicate via a Novell local area network. The Televideo will serve as host to the 940 MB WORM optical disk drive and a 150 MB cartridge tape drive. The DELL 316 will serve as host to the Transputer (parallel processing) boards, of which we have purchased three, each with four T-800 transputers and a fast 80 MB SCSI disk drive. Both the DELL 310 and DELL 316 have VGA color monitors and are configured with 80387 numeric co-processors.

The PC radar hardware was successfully interfaced with the NOAA receiver and transmitter subsystems at the USU Bear Lake Observatory in January 1990 and ionospheric measurements have been made periodically since that time. Typical ionograms from our Observatory are shown in Figure 2. Here, a linear frequency scale from 1 to 20 MHz is plotted (top panel) as a function of virtual range. The three panels below each ionogram depict represent the 'sky map' projection of echo location ( $\pm 250$  km) and a projection of echo height onto the north-south and east-west planes through the receiver location. The two ionograms shown here were acquired at 2109 LT (June 11, 1990) and 0604 LT (June 12, 1990). Note that these displays are dot matrix printer dumps of color screens, where color is used to denote the amplitude of the echo. A fixed-frequency

sounding at 4.2 MHz is presented in Figure 3. In this diagram, the echo amplitude and phase are plotted as a function of time (60 seconds in this example). The format of the lower three panels is the same as in Figure 2. Operation of the radar at the Bear Lake site has been supported by NASA from whom we obtained a modest grant for ground-based measurements in support of the Soviet ACTIVNY satellite campaign.

Figures 4 and 5 show photographs of the computer system used for control of the radar. At the far left of Figure 4 is a power supply used to provide voltage to the ADC board and adjacent to the power supply are the WORM drive, the system monitor and the DELL 310 control computer (sitting on top of an expansion chassis). A close-up view of the DELL 310 is shown in Figure 5. The ADC, SKY and CRAM boards occupy four of the five left-most slots in the computer chassis.

While the integration of the major hardware components has been essentially completed, we are still in the process of software development, mainly in the design and implementation of software for parallel processing. The software for the operation of the radar was provided by LANL, although we have both enhanced that software and used it as a starting point for other types of analysis routines. We anticipate that software development will be an ongoing process. For example, during the summer of 1990 two undergraduate students (one from Stanford University and another from the University of Alabama at Huntsville) will participate in software development. Their participation is funded through a Research Experience for Undergraduates program sponsored by the National Science Foundation. Furthermore, the Air Force Institute of Technology and the Rocky Mountain Space Consortium (a NASA funded program) will support an Air Force officer while he obtains a Master's degree in Electrical Engineering, beginning in September 1990.

Over the course of the implementation of this instrumentation grant, two graduate students in the Electrical Engineering Department have been supported by matching funds supplied by the Research Office at Utah State University. Mr. Rajeev Danank will be obtaining his M.S.E.E. degree as a result of his involvement in the program and Mr. Jun Yuan Deng has begun work toward his Ph.D. Mr. Deng will continue his Ph.D. work, using the radar project as his research topic, through NASA monies. The Transputer hardware acquired for the radar system has been utilized in an ongoing research program within the Electrical Engineering Department under the direction of Dr. G.S. Stiles. Two graduate students utilized our Transputer hardware and program compilers in their M.S. thesis research (*Jong, 1989; Hu, 1990*). The results of this research were presented at an international transputer meeting (*Jong and Stiles, 1989*).

Professor Xu Zhiqian, a visiting Professor from the University of Electronic Science and Technology of China, joined our radar group in December 1989 and has studied the application of coded pulse techniques to the PC radar. He has recently simulated a complementary phase code



scheme in software and is in the process of developing a working implementation of this coding scheme.

#### *WORK IN PROGRESS*

Much of our current research activity is focussed on enhancing the existing software (both operating and analysis) by adding windows, menus and mouse control. We are in the preliminary stages of developing transputer based codes (in the parallel FORTRAN and C languages) for application to real-height analysis, automatic scaling, adaptive system control and ray tracing. Operating environments and language compilers for parallel languages and the Transputer in particular have been purchased under the AFOSR instrumentation grant and have been evaluated.

In addition to the application of parallel processing algorithms, our future research interests include: 1) advanced signal processing algorithms using coded pulses; 2) oblique sounding between Utah and New Mexico; 3) backscatter sounding in the HF regime; 4) realtime analysis, modelling and control.

Salary monies were not provided under AFOSR University Instrumentation funding and support for the Principal Investigator was obtained from NSF and NASA funded projects and the Space Dynamics Laboratory and Research Office at Utah State University. Dr. G.S. Stiles (a co-investigator) participation has been supported by the Electrical Engineering Department. We are actively pursuing external funding support for the continued development and operation of the radar system. As noted, a small grant was obtained from NASA for ground-based support of a Soviet VLF satellite mission. Proposals have been submitted and are in preparation for submission to the National Science Foundation.

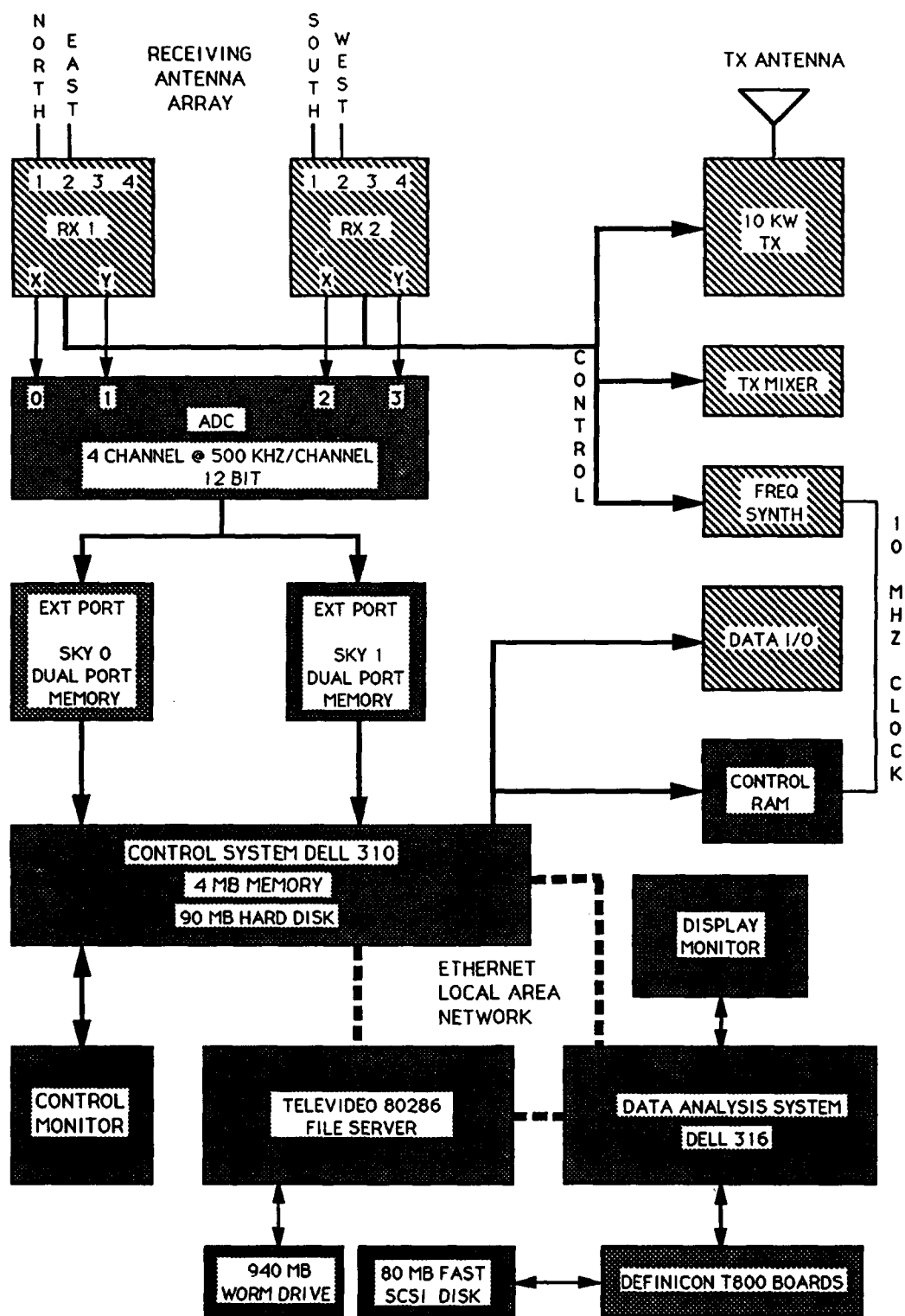
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## FIGURE CAPTIONS

- Figure 1 A schematic diagram showing the hardware components acquired under auspices of the Defense University Research Instrumentation Program, grant number AFOSR-89-0094 to Utah State University.
- Figure 2 Digital ionograms acquired at the Utah State University Bear Lake Observatory using the PC radar system (see text for explanation).
- Figure 3 A fixed-frequency kinesonde mode sounding acquired at the Bear Lake Observatory on June 10, 1990 (see text for explanation).
- Figure 4 A photograph showing the radar control computer (a DELL 310) and associated components in operation at the USU Bear Lake Observatory.
- Figure 5 A close-up view of the radar control computer showing the data acquisition, ADC and CRAM boards which reside on the system bus of the DELL 310.



USU HF RADAR HARDWARE CONFIGURATION

Figure 1

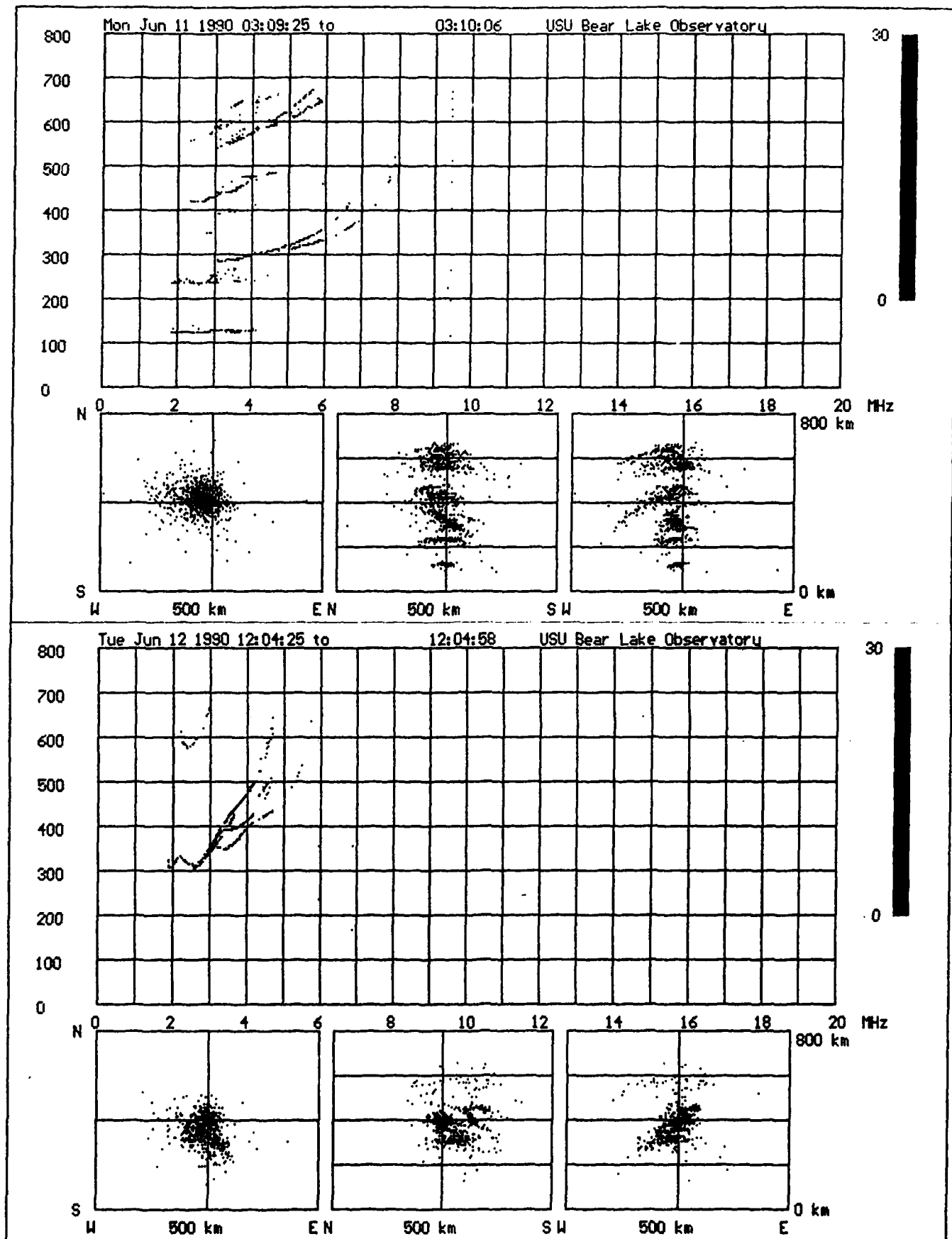


Figure 2

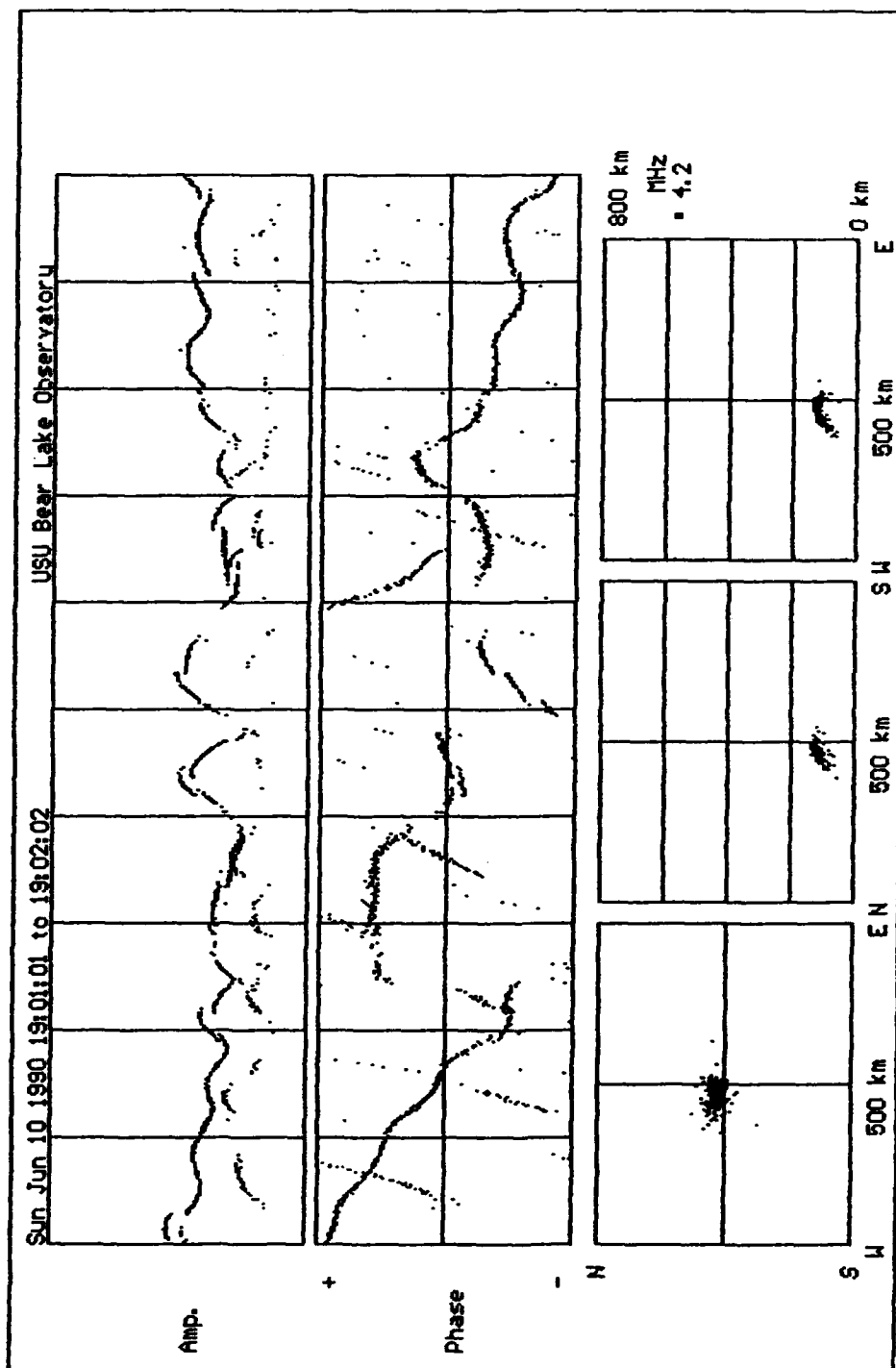


Figure 3